Masters Program in Geospatial Technologies

Measuring Air Quality with Low-Cost Sensors in Citizen Science Applications

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Measuring Air Quality with Low-Cost Sensors in Citizen Science Applications

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DECLARATION

I hereby declare that I am the sole author of this Master Thesis entitled "Measuring Air Quality with Low-Cost Sensors in Citizen Science Applications".

I declare that this thesis is submitted in support of candidature for the Master of Science in Geospatial Technologies and that it has not been submitted for any other academic or non-academic institution.

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Jana Lodi Martins

Muenster, 24.02.2017

ABSTRACT

Air pollution is unquestionably a public health emergency, and the rates of pollution continue to rise at an alarming rate in cities all over the world. Nevertheless, the traditional monitoring equipment is very expensive, and the available measurements are not sufficient to precisely classify air quality in several locations in a city. Recent advancements in air quality measuring technology provide a potential opportunity to increase the air quality data, and to raise public awareness of health issues arising from air pollution. This study focuses on the development and evaluation of a new prototype for the monitoring of fine particulate matter (PM2.5). It describes the design approach and the evaluation methods, in which a series of field experiments were conducted to evaluate the performance of the prototype and of a commercial low-cost device in comparison with a reference monitor. The results showed that the prototype presented a good performance in environments with a high variation of particle concentrations (variations above 100µg/m^3), such as cooking-environments and exposure to cigarette smoke, for most of the experiments (R^2 = 0.55-0.85). However, their agreement was very poor in environments without high variability of particle concentrations. The performance comparison between identical sensors purchased in the same year revealed a very high agreement (R^2 = 0.92), but prototypes which utilized sensors acquired in different years presented a very weak correlation in most of the experiments. The analysis of the commercial low-cost device's performance revealed a moderate to strong linear correlation with the reference monitor in all the experiments (R= 0.51-0.93); this study also demonstrates that the maximum limit of detection of the device was much lower than the value given by the manufacturer (approximately 180µg/m^3, in contrast to the value of 400µg/m^3). For applications of real-time measurements, the prototype developed in this research may be especially utilized as indicative of PM2.5 hotspots and trends in ambient conditions, primarily in residences, monitoring the frequency and duration of high exposure events, such as cooking, smoking, and biomass burning. Nevertheless, this research demonstrates the necessity for individual sensor performance testing prior to field use, and that presumptions about the representativeness of measurements of PM2.5 carried out by low-cost sensors should be made with caution.

ACRONYMS

API - Application Program Interface

AQE - Air Quality Egg

AQI - Air Quality Index

CO - Carbon monoxide

CSV - Comma Separated Value

DIY - Do-It-Yourself

EPA - United States Environmental Protection Agency

EU – European Union

FEM - Federal Equivalent Method

GPS - Global Positioning System

ifgi - Institute for Geoinformatics

LANUV - Landesamt für Natur, Umwelt und Verbraucherschutz

LED - Light-emitting diode

Pb - Lead

NO - Nitrogen oxide

NO2 - Nitrogen dioxide

NOX - Mono-nitrogen oxides (NO and NO2)

O3 - Ozone

PM - Particulate matter

PM10 - Coarse particulate matter

PM2.5 - Fine particulate matter

Ppb - Parts per billion

Ppm - Parts per million

R - Linear correlation coefficient

R^2 - Coefficient of determination

RTC - Real-Time-Clock

SO2 - Sulfur Dioxide

VGI - Volunteered Geographic Information

WAQI - World Air Quality Index

WHO - World Health Organization

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1 INTRODUCTION

According to the World Health Organization (WHO), air pollution is the world´s largest environmental health risk, and it is estimated that around 1.4 billion urban residents in the world live in areas with air pollution above recommended air quality guidelines (World-Health-Organization, 2016). Air pollution affects all regions, socio-economic and age groups. The organization assesses the global exposure to air pollution based on the concentration of fine particulate matter (PM2.5), and Figure 1 presents the location of the monitoring stations and PM2.5 concentration according to the database of the organization.

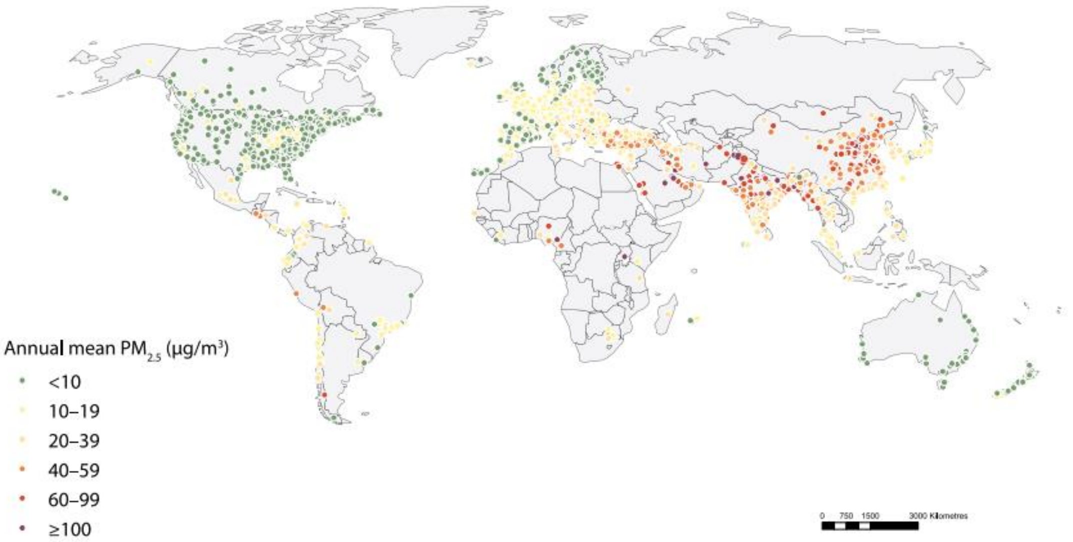

Figure 1: Location of the monitoring stations and PM2.5 concentration according to the WHO database (World Health Organization, 2016)

Although some government agencies monitor and publish metropolitan air quality data and indexes, there are several limitations to this approach. In general, the spatial resolution of the pollution sampling is very poor and frequently the use of mathematical models is necessary to estimate pollutant concentrations over vast sections of the cities, which can be both inaccurate and complex (Sivaraman et al, 2013). Furthermore, the traditional monitoring equipment necessary to meet the standards established by national regulations for air quality has high costs of acquisition and maintenance (Devarakonda et al., 2013; Velasco et al, 2016).

In this context, the low-cost air quality measuring systems for participatory sensing emerge as a potential solution for the worldwide air quality measuring issue. These systems are small devices that include sensors capable of collecting and transmitting environmental measurements in real time, with low costs and involving participation by citizens. These devices can increase the data density of measurements and complement the already existing official air quality monitoring systems of the cities (Velasco et al., 2016). Beyond that, these platforms can effectively disseminate pollution information to citizens and raise public awareness of health issues arising from air pollution.

However, while public interest is quickly growing, the data quality of the air sensors remains uncertain, particularly that of commercial devices which may be utilized by citizens and communities to measure air quality in their local environments (Jiao et al., 2016). Further research on low-cost air quality sensors is essential, in order to get additional insight into the specific influence of environmental and operational conditions on the performance of low-cost sensors (Holstius, 2014).

In order to advance the research on the topic, this study will focus on the development of a new prototype for the monitoring of fine particulate matter (PM2.5). This document describes the design approach and process up to the point of building and testing the instrument. It presents the results of an evaluation of the developed prototype and of a commercial low-cost device (AirBeam) in a series of field experiments, which validated the performances of the instruments with a reference monitor (DustTrak).

1.1 AIM AND SPECIFIC OBJECTIVES

1.1.1 Aim

The aim of this work is to develop a low-cost prototype for the monitoring of fine particulate matter (PM2.5) and compare its performance with a reference monitor and with an existing low-cost device. Field experiments in the city of Münster, Germany, were undertaken in order to characterize its performance.

Research Question: Under which circumstances is it possible to obtain a good performance of low-cost devices designed to measure fine particulate matter (PM2.5) in Citizen Science Applications?

1.1.2 Specific Objectives

- Perform a comprehensive literature review on air quality monitoring, citizen science applications in air quality and on the European legislation for air quality itself.
- Investigate the existing low-cost citizen science air quality measuring systems in the world and its user interface online platforms for the visualization of air quality data.
- Develop a prototype for PM2.5 monitoring, by using low-cost components.

- Evaluate the performance of the prototype in different environments and under different conditions, through comparison with a reference instrument (DustTrak).
- Compare the performance of identical PM2.5 sensors purchased in similar and in different years, to understand the reproducibility of the sensor performance.
- Analyze the performance of a commercial low-cost PM2.5 instrument (AirBeam).

1.2 CONTEXT OF THIS RESEARCH

This study is a part of the SenseBox Project, of the Institute for Geoinformatics, University of Münster. The SenseBox is a low-cost citizen science system that enables the users to make location-based environmental measurements collected by sensors (SenseBox, 2017). Currently, the system collects data such as temperature, humidity, air pressure and noise and publishes it on an online open platform. A previous study was performed in the Institute to include pollutant measurement sensors in the device, but it found several limitations, e.g., some sensors were not able to measure very low values of pollutant concentrations, and the same type of sensors presented different results for equal locations and equal time (Pesch, 2015).

1.3 THESIS STRUCTURE

This Thesis consists of six chapters in total. In Chapter 1, objectives and research question are presented. After that, the theoretical background is stated in Chapter 2, indicating essential fundamentals of air quality and citizen science. Chapter 3 introduces the methodology for the development of the prototype and the realization of the experiments. Field tests are a central task to evaluate the performance of the developed prototype. Chapter 4 focuses on the results of the experiments conducted in different environments. The main findings and limitations of this study are presented in Chapter 5. Finally, Chapter 6 presents the conclusions of this Master’s Thesis and discusses the outcomes for possible future work.

2 THEORETICAL BACKGROUND

2.1 AIR QUALITY

2.1.1 Air Pollutants

According to the United States Environmental Protection Agency (EPA), air pollution involves a complex combination of different chemical components in different forms in the atmosphere: solid particles, liquid droplets, and gases. Some of these pollutants are temporarily in the air (i.e. hours to days), while others are long-lasting (i.e. years). The factors which influence the amount of time that a pollutant remains in the atmosphere are its reactivity with other substances and its propensity to deposit on a surface; these influences are affected by the pollutant composition and weather conditions including precipitation, temperature, wind and sunlight (Williams et al., 2014).

Pollutants in the atmosphere are emitted by an extensive variety of sources including natural occurrences and those of man-made origin. Examples for natural sources are dust storms, forest fires, and volcanic eruptions, while man-made sources include vehicles, gas facilities, and industries. The primary pollutants are released directly from a source (examples: carbon monoxide [CO], nitrogen dioxide [NO2], particulate matter [PM] and sulfur dioxide [SO2]); while the secondary pollutants derive from others through chemical reactions (examples: ozone [O3] and some forms of particulate matter). Table 1 presents a summary of some common air pollutants, as well as relevant information for detecting these pollutants in the air.

Table 1: Summary of some common air pollutants (Adapted from EPA, 2014)

Air Pollutant of Interest	Type	Source Example	Useful Detection Limits	Range to Expect
Fine particulate matter (PM2.5)	Primary and Secondary	Fuel combustion (mobile sources, electric utilities, industrial processes), dust, agriculture, fires	5μg/m³ (24-hr)	0 - 40 μg/m³ (24-hr)
Coarse particulate matter (PM10)	Primary and Secondary	Fuel combustion (mobile sources, industrial processes), dust, agriculture, fires	10 μg/m³ (24-hr)	0 -100 μg/m³ (24-hr)
Carbon Monoxide (CO)	Primary	Fuel combustion (mobile sources, industrial processes)	0.1 ppm	0 - 0.3 ppm
Nitrogen dioxide (NO2)	Primary and Secondary	Fuel combustion (mobile sources, electric utilities, off-road equipment)	10 ppb	0 - 50 ppb
Ozone (O3)	Secondary	Formed via UV (sunlight) and pressure of other key pollutants	10 ppb	0 - 150 ppb
Sulfur Dioxide (SO2)	Primary	Fuel combustion (electric utilities, industrial processes)	10 ppb	0 - 100 ppb
Lead (Pb)	Primary	Smelting, aviation gasoline, waste incinerators, electric utilities	0.05 μg/m³ (24-hr)	0 - 0.1 μg/m³ (24-hr)

Air pollution has been associated with several issues, such as health conditions, environmental and climate effects. According to the EPA, there are six main pollutants of concern due to their huge impact, identified by the organization as the "criteria pollutant": particulate matter (PM), carbon monoxide (CO), ozone (O3), nitrogen dioxide (NO2), sulfur dioxide (SO2), and lead (Pb) (EPA, 2016). Table 2 summarizes potential effects associated with the criteria pollutants.

Table 2: Potential effects of common air pollutants (Adapted from EPA, 2014)

Pollutant	Potential Health Effects	Environmental and Climate Effects
Ozone (O3)	• Chest pain, coughing, throat irritation, and congestion; • Worsens bronchitis, emphysema, and asthma; • Reduces lung function and inflames the linings of the lungs.	• Damages vegetation by injuring leaves, reducing photosynthesis, impairing reproduction and growth, and decreasing crop yields. • Ozone is a greenhouse gas that contributes to the warming of the atmosphere.
Particulate Matter (PM2.5 and PM10)	• Premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, and increased respiratory problems.	• Impairs visibility, affects ecosystem processes and can deposit onto surfaces damaging materials; • Climate impacts: net cooling and warming
Lead (Pb)	• Damages the developing nervous system, resulting in IQ loss and negative impacts on children's learning, memory, and behavior; • In adults: cardiovascular and renal effects and anemia.	• Losses in biodiversity, changes in community composition, decreased growth and reproductive rates in plants and animals, and neurological effects in vertebrates.
Sulfur Dioxide (SO2)	• Aggravates pre-existing respiratory disease in asthmatics leading to symptoms such as a cough, wheeze, and chest tightness.	• Contributes to the acidification of soil and surface water; • Causes injury to vegetation and losses of local species in terrestrial and aquatic systems; • Contributes to particle formation, which has a net cooling effect on the atmosphere.
Nitrogen Dioxide (NO2)	• Aggravates respiratory symptoms, increases hospital admissions, particularly in asthmatics, children, and older adults; • Increases susceptibility to respiratory infection.	• Contributes to the acidification and nutrient enrichment of soil and surface water; • Leads to oxygen depletion in waters, losses of plants and animals, and changes in biodiversity losses. .
Carbon Monoxide (CO)	• Reduces the amount of oxygen reaching the body's organs and tissues; • Aggravates heart diseases.	• Contributes to the formation of ozone and CO2, greenhouse gases that warm the atmosphere.

2.1.2 Air Quality Legislation in Europe

The most recent legislation relating to air quality in Europe is the EU Directive 2008/50/EC of the 21th May of 2008. The Directive consolidated several earlier directives and set objectives for some pollutants which are harmful to public health and the environment, requiring the Member States to:

- Monitor and assess air quality to ensure that it meets these objectives;
- Report to the Commission and the public the results of this monitoring and assessment;
- Prepare and implement air quality plans containing measures to achieve the objectives (EU, 2008).

The Directive aims to protect human health and the environment, its main significance being to combat pollutants' emissions at their origin and to identify measures to decrease emissions. As part of the policy, limits for the pollutants were determined. Table 3 presents the most important limits for compliance with the Directive. The limit values for the individual parameters are divided into annual averages and/or a specific number of hours.

Table 3: Important limit values according to Directive 2008/50/EC

Pollutant	Concentration	Averaging period	Permitted exceedances each year
Fine particles (PM2.5)	20 µg/m³	1 year	n/a
Sulfur dioxide (SO_2)	350 µg/m³	1 hour	24
	125 µg/m³	24 hours	3
Nitrogen dioxide (NO_2)	200 µg/m³	1 hour	18
	40 µg/m³	1 year	n/a
PM10	50 µg/m³	24 hours	35
	40 µg/m³	1 year	n/a
Lead (Pb)	0.5 µg/m³	1 year	n/a
Carbon monoxide (CO)	10 mg/m³	Maximum daily 8-hour mean	n/a
Ozone	120 µg/m³	Maximum daily 8-hour mean	25 days averaged over 3 years

Member States shall collect, interchange and propagate air quality information in order to understand better the impacts of air pollution and develop appropriate strategies. Information on concentrations of all regulated pollutants in ambient air must also be readily accessible to the public.

The Directive also outlines the use of "indicative measurements" that in specific conditions can be used to supplement "fixed" or "regulatory" measurements, in order to provide information on the spatial variability of pollutant concentrations. However, no provision is made for them to be used independently for regulatory purposes. These supplementary measurements have less stringent requirements for data quality, as can be seen in Table 4.

Table 4: Data quality objectives for ambient air quality assessment (Adapted from EU, 2008)

Type of Measurement	Maximum Uncertainty Allowable in Pollutant Measurement			
	SO2, NOX, CO	Benzene	PM, Lead	Ozone
Regulatory (fixed)	15%	25%	25%	15%
Supplemental (indicative)	25%	30%	50%	30%

Additionally, the use of supplementary techniques may also allow the reduction of the mandatory amount of fixed sampling points.

2.1.3 Air Quality Index

Air quality indexes are mostly used for citizen awareness purposes, i.e., to inform citizens about the level of air pollution severity in a simplified approach (Villani et al., 2016).

The Air Quality Index (AQI) was developed by the EPA and is currently the most widespread air index in the world. Such index reports how clean or unhealthy the air is, and which related health effects may be a concern. The AQI emphasizes the health effects people may experience within a few hours or days after breathing unhealthy air. The index considers the following pollutants: ground-level ozone, particulate matter, carbon monoxide, and sulfur dioxide (USEPA, 2014).

The AQI is divided into six levels of health concern varying in a scale of 0-500, according to Figure 2. The higher the AQI value, the greater the concentration of air pollution. In addition to a pure value, the AQI also offers a behavioral recommendation and a risk assessment for different groups of people. For instance, AQI values lower than 50 represent good air quality with little harm or no potential harm to public health, while AQI values over 300 represent a hazardous level of air quality and the entire population may experience serious health effects.

Air Quality Index Levels of Health Concern	Numerical Value	Meaning
Good	0 to 50	Air quality is considered satisfactory, and air pollution poses little or no risk
Moderate	51 to 100	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
Unhealthy	151 to 200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
Very Unhealthy	201 to 300	Health warnings of emergency conditions. The entire population is more likely to be affected.
Hazardous	301 to 500	Health alert: everyone may experience more serious health effects

Figure 2: AQI levels of health concern (USEPA, 2014)

The website http://waqi.info/ presents an interactive map with the AQI derived from available information in stations worldwide (WAQI, 2017). The data relies on monitoring stations run by the governments, thus, no data from Do-It-Yourself (DIY) stations or similar are displayed and evaluated. The website is pictured in Figure 3.

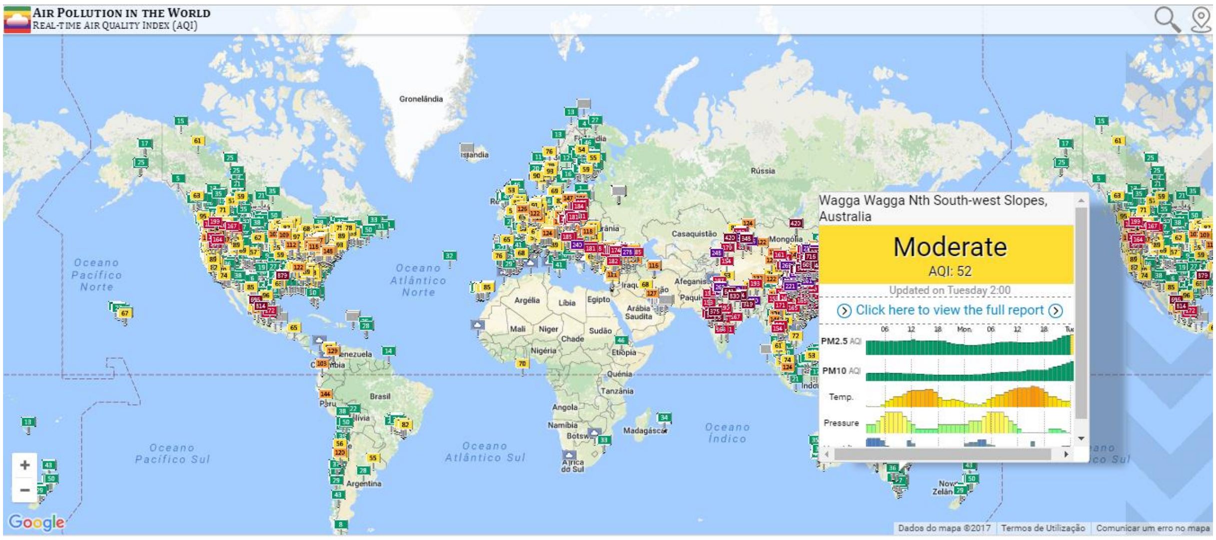

Figure 3: Real Time Air Quality Index website

2.2 CITIZEN SCIENCE IN AIR QUALITY

Citizen Science is the worldwide engagement of millions of individuals, many of them nonscientists, in collecting, categorizing, transcribing, or analyzing scientific data. Projects involving citizens include a range of topics from microbiomes to native bees to air quality (Bonney et al., 2014). Although the term “citizen science” itself has only emerged in recent years, much of the existing understanding of the natural environment already results from data that has been collected, transcribed, or processed by non-scientists. In the last two decades, the number of citizen science projects has vastly expanded, as well as scientific reports and articles resulting from their data.

The field of citizen science has been rapidly growing given the advancements in the communication and information technologies. Microphones and cameras on smartphones can record data, while mobile phone tracking, GPS, and other technologies can provide location and time-synchronization (Burke et al., 2006). Moreover, the second generation of Internet, the Web 2.0, provided services for people to collaborate and share information online (Murugesan, 2007). Goodchild introduced the term “volunteered geographic information” to describe the web phenomenon of user generated content and dissemination of geographic data provided voluntarily by individuals (Goodchild, 2006).

2.2.1 Sensors for Air Quality

Recent technologies on low-cost air quality sensors have created portable and low-cost air sensor devices that have the potential to generate a dense amount of air quality data through individual use or projects in a large network of sensors (Bartonova et al., 2015; Neophytou et al., 2015). Researchers are already utilizing low-cost sensors in exploratory research, to assess the geographical variability of urban air quality (Gao et al., 2015; Levy, 2014).

2.2.1.1 Sensor Operation

There are three main types of air quality sensors, based on their principle of operation: metal-oxide, electrochemical and optical sensors. The sensing properties in metal-oxide sensors are based on the reaction between the semiconductor metal-oxide and the gases in the atmosphere, which results in changes in conductivity. This response is measured and associated with the pollutant concentration. Electrochemical sensors operate by reacting with the gas of interest and producing an electrical signal proportional to the gas concentration. The last type of sensor is the optical one, in which a light receptor detects the light scattered by particles in the airstream, and produces a low pulse as the output. The particle concentration is estimated based on the percentage of time the sensor is reporting a low pulse versus a curve of concentration provided by the manufacturer (Yunusa et al, 2014; SCAQ, 2017).

Currently, low-cost sensor instruments usually utilize metal-oxide or electrochemical sensors for the measurements of gas pollutants such as CO, NO2, NO and O3. On the other hand, commercial PM sensor devices normally use laser-based or light-emitting diode (LED)-based optical detectors of particles (Jiao et al., 2016), as the one used in this study. At present, there are no commercially available devices which utilize direct mass measurement of PM, but ongoing research aims to develop a true mass measurement (Paprotny et al., 2013).

2.2.1.2 Potential Uses and Assessment of Low-cost Sensors

The EPA proposes several potential non-regulatory application areas for air quality sensors, which are illustrated in Table 5 (Williams et al., 2014).

Table 5: Description of potential uses for low-cost air sensors (EPA, 2014)

Application	Description
Research	Scientific studies aimed at discovering new information about air pollution.
Personal Exposure Monitoring	Monitoring the air quality that a single individual is exposed to while doing normal activities.
Supplementing Existing Monitoring Data	Placing sensors within an existing state/local regulatory monitoring area to fill in coverage.
Source Identification and Characterization	Establishing possible emission sources by monitoring near the suspected source.
Education	Using sensors in educational settings for science, technology, engineering, and math lessons.
Information/Awareness	Using sensors for informal air quality awareness

An important aspect of the emerging low-cost technology is the method of assessment of the performance of the sensors. Although environmental agencies as EPA have a well-defined method for approving technologies for use in the regulatory process, at present there are no clear defined or universally accepted criteria to evaluate the sensors, i.e., there are no official criteria which provide a “pass” or “fail”, or alternative grading scheme to assess a particular sensor model. According to the EPA, developing such criteria will be a challenge, considering the diversity of potential applications and related performance goals (Jiao et al., 2016).

The EPA in its Air Sensor Guidebook suggests performance goals for the sensors according to the potential application, presented in Table 6. The suggestions were defined based on expert interviews, group meetings, and peer-reviewed and government related literature, and are an initial guideline to be improved over time (Williams et al., 2014).

Table 6: Suggested Performance Goals for Sensors for several applications by EPA (EPA, 2014)

	Application area	Pollutants	Precision	Data Completeness	Rationale
I	Education and Information	All	> 50%	≥ 50%	Measurement error is not as important as simply demonstrating that the pollutant exists in some wide range of concentration.
II	Hotspot Identification and Characterization	All	> 30%	≥ 75%	Higher data quality is needed here to ensure that not only does the pollutant of interest exist in the local atmosphere, but also at a concentration that is close to its true value.
III	Supplemental Monitoring	Criteria pollutants, Air Toxics	> 20%	≥ 80%	Supplemental monitoring might have value in providing additional air quality data to complement existing monitors. It must be of sufficient quality to ensure that the additional information is helping to "fill in" monitoring gaps rather than making the situation less understood.
IV	Personal Exposure	All	> 30%	≥ 80%	Many factors can influence personal exposures to air pollutants. Lower precision rates make it difficult to understand how, when, and why personal exposures have occurred.
V	Regulatory Monitoring	O3	> 7%	≥ 75%	Precise measurements are needed to ensure high-quality data to meet regulatory requirements.
		CO, SO2	> 10%		
		NO2	> 15%		
		PM2.5, PM10	> 10%		

Furthermore, an important step to assure the data quality of the sensors is the calibration at periodic intervals, in order to assess the instrument's response to changes in concentrations. In the calibration procedure, the instrument's measurements are compared to a reference value under similar environmental and operational conditions as those in which the device will collect measurements, as many sensors are highly influenced by these conditions (Williams et al., 2014).

2.2.2 Existing Air Quality Platforms

In the context of citizen science, there are several projects which collect environmental data. In most of them, environmental data is collected by low-cost sensors and then sent over the Internet to a data platform for data visualization. Examples are the AirQualityEgg, Smart Citizen, Air Casting, and the AirSensEURProject. In the following, some of these projects will be briefly presented.

2.2.2.1 Air Quality Egg

The Air Quality Egg (AQE) project aims to give citizens a way to participate in the conversation about air quality. It consists of sensing devices based on open-source hardware components and a web platform for publishing the collected data (Air Quality Egg, 2017). The device can measure concentrations of carbon monoxide and nitrogen dioxide as well as temperature and relative humidity. The enclosure indicates the air quality with different light colors. The hardware device and web platform with a selected station are shown in Figure 4.

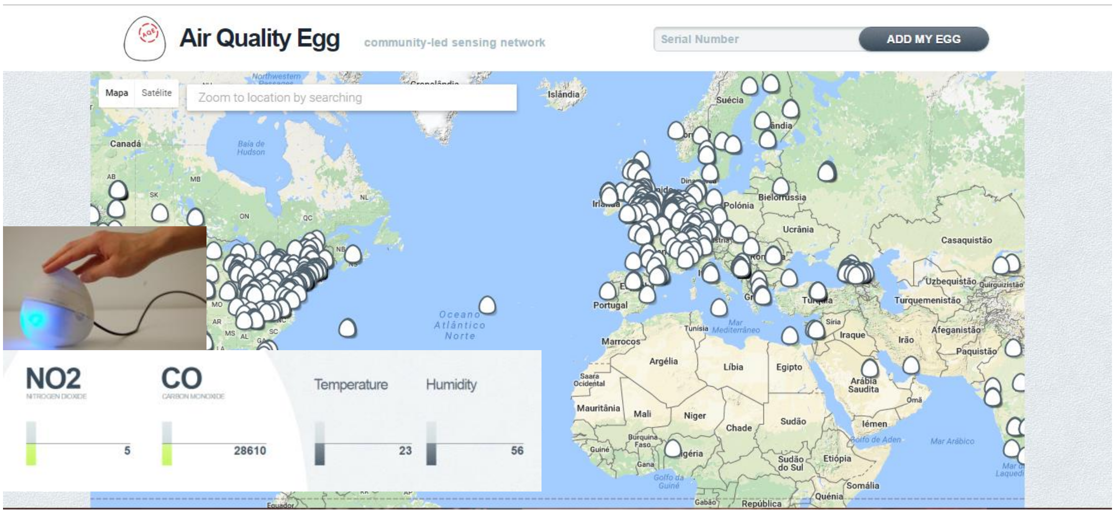

Figure 4: Air Quality Egg device and web platform

2.2.2.2 Smart Citizen

The Smart Citizen is another project which uses open source technology for citizens' participation. Similar to the AQE approach, the platform allows participants to measure and make air quality data public. Its sensors are able to measure carbon monoxide and nitrogen dioxide concentrations, as well as temperature, brightness, humidity and noise. After configuration and deployment, the device sends data samples to a web platform, in which the data can be accessed on a map interface. Moreover, the server application offers an Application Program Interface (API), which can be used to build custom applications on top of the Smart Citizen hardware and platform (FabLab Barcelona, 2017). The hardware device and web platform are pictured in Figure 5.

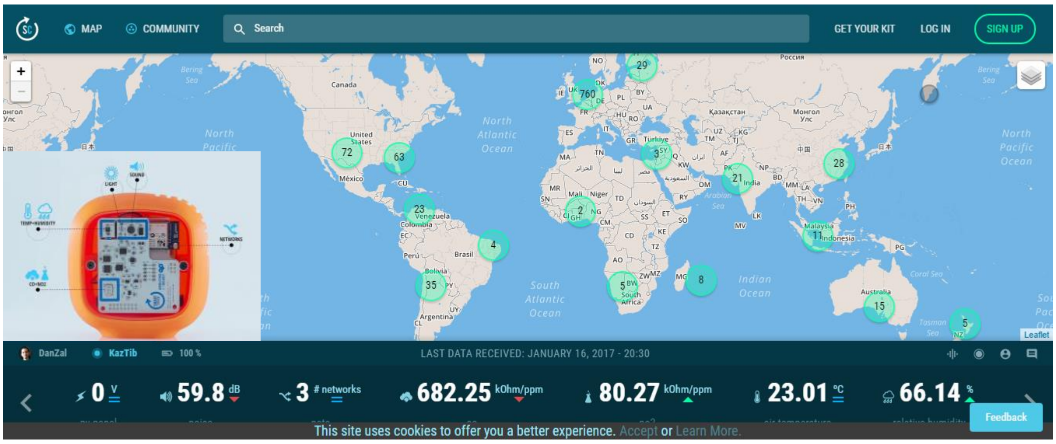

Figure 5: Smart Citizen device and web platform

2.2.2.3 Air Casting

Another open-source platform for collecting, displaying, and sharing environmental data is the Air Casting. The project includes a palm-sized air quality monitor called AirBeam which is able to measure PM2.5, temperature, humidity and noise. Via Bluetooth, the measurements are sent to the AirCasting Android app, which maps and graphs the data in real time on the smartphone. Then, the data is transmitted to the AirCasting website, and the data is crowdsourced with data from other devices and heat maps are generate to indicate where PM2.5 concentrations are highest and lowest (AirCasting, 2017). As an open-source platform, the project also allows modifying its components, to include other sensors, and to transmit the data to other websites or apps. The hardware device and web platform are pictured in Figure 6.

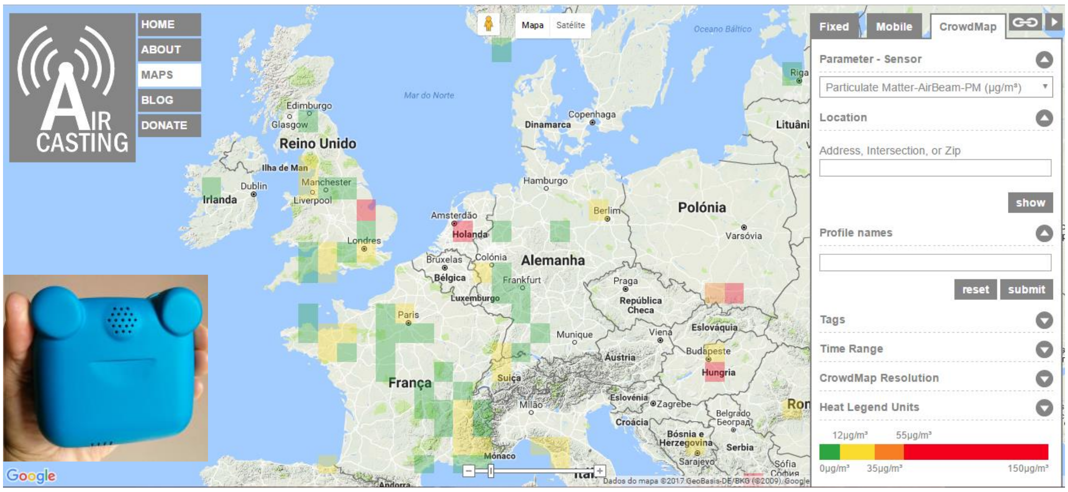

Figure 6: Air Casting device and web platform

2.2.3 Comparison of Online Platforms

Table 7 presents a comparison between several online platforms for air quality data visualization, including the following projects: Air Casting, Smart Citizen and Air Quality Egg.

Table 7: Comparison between existing air quality platforms

	Air Casting	Smart Citizen	Air Quality Egg
Parameters	PM2.5 (μg/m³), temperature (ºC) and humidity (%)	NO2 (kOhm/ppm), CO (kOhm/ppm), light intensity (Lux), relative humidity (%), air temperature (ºC), sound levels (dB) and battery (%)	NO2, CO, temperature and humidity
"Openness" of the projects	On the website, the data displayed is only from the AirCasting devices. It is not possible to include other devices. The AirCasting app and website code is available on GitHub.	On the website, the data displayed is only from the Smart Citizen devices. It is not possible to include other devices. The server application offers an Application Program Interface (API), which can be used to build custom applications on top of the Smart Citizen hardware and platform	The project allows modifying its components, to include other sensors, and to transmit the data to other websites or apps. It is not possible to include data from other devices on the platform, only from Air Quality Egg devices.
Operation	The device collects measurements approximately once a second and sends them via Bluetooth to the smartphone, through an Android application. The app maps and graphs the data collected in real time and, at the end of each session, the data is sent to the AirCasting website.	The device collects data and sends it to a computer/ Android App through the wireless module installed on the data-processing board.	The device collects the data and sends it via Wi-Fi to the cloud at Opensensors.io, an open data service, which both stores and provides free access to the data. Then, the data is sent to the AQ Egg website, and to Xively, where it is possible to see graphs and other visualizations of the data.
Visualization of the data	The data from different AirCasting devices is the base for generating heat maps indicating the PM2.5 concentration. The visualization is based on grids; each square's color corresponds to the average of all the measurements recorded in that area. It is possible to define the scale of the heat legend units on the website, changing the colors of the grids depending on the scale. There are filters for parameter/sensor/location/profile name/tags/time range/resolution.	There is no data interpolation, so, there is no estimation of pollutant-concentration for non-measured areas on the online map. There are filters with which it is possible to define the kind of location (indoor/outdoor) and the state of connectivity (online/offline). The units of the measurements are not clearly defined. On the website, it is informed that both units (kOhm and ppm) are utilized for the pollutants' concentration, but there is no information about methods of conversion between these units.	The website displays the location of the devices and the last measured values, but these values are not associated with any units; so it is difficult to interpret the values and, consequentially, the air quality condition.

Download the data	The platform does not present any download option.	The platform does not present any download option.	The platform does not present any download option.
Historical data	The platform displays historical values.	The platform displays historical values.	The platform does not display historical values.

3 METHODOLOGY

The following chapter describes the methodological approach adopted in this thesis, summarized in Figure 7. The following sections of this chapter will describe each of the steps stated in the figure. First, the development of the prototype will be described, which includes the prototype components, its operation, and the case design. The second section focuses on the experiments, and the third session presents the methods for treatment and assessment of the collected data.

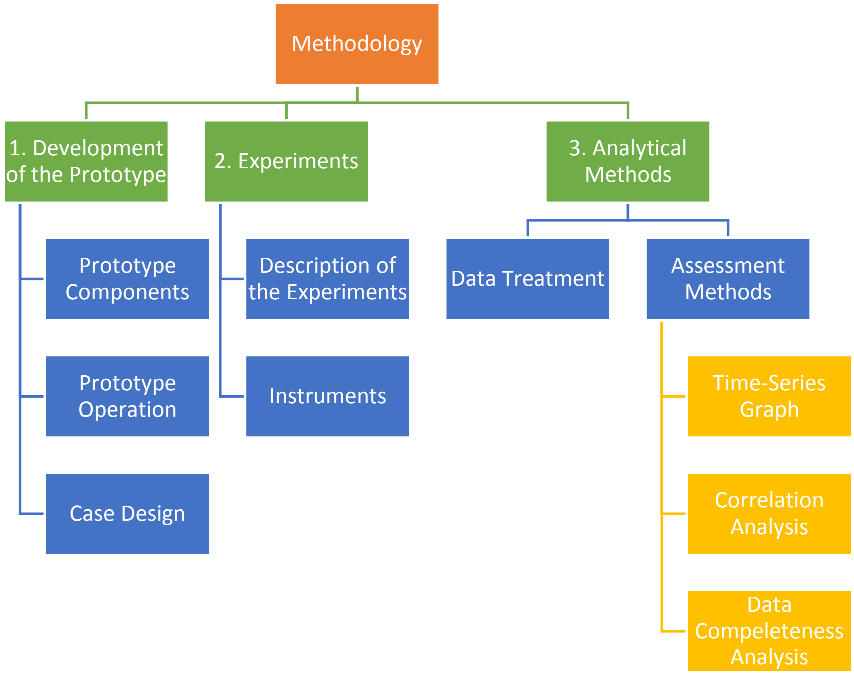

Figure 7: Methodological Approach

3.1 DEVELOPMENT OF THE PROTOTYPE

3.1.1 Prototype Components

An illustration of the prototype is shown in Figure 8, and a list of all the components used in the prototype and its approximate costs are presented in Table 8.

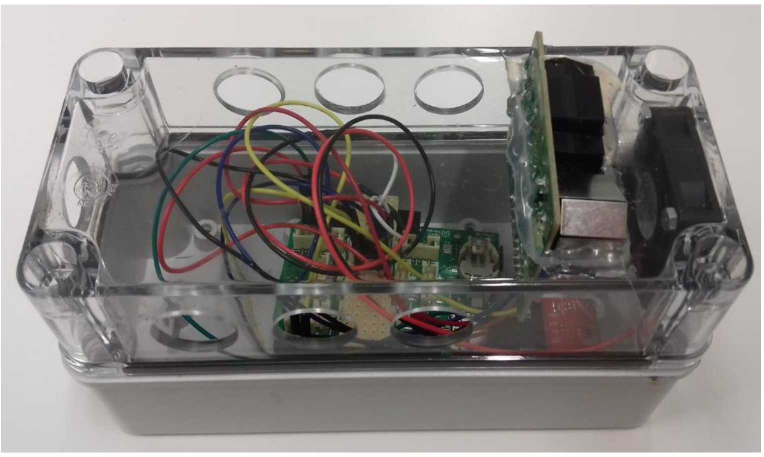

Figure 8: Prototype

Table 8: Components of the prototype

Nr.	Components:	Prices
1	Arduino Uno Microprocessor	24 €
2	SenseBox – Shield (connector board)	10 €
3	Shinyei PPD42NS (PM2.5)	17 €
4	HC1000 (temperature and humidity)	14 €
5	microSD-Card	5 €
6	FAN-4010 5V	2 €
7	External Battery	10 €
8	Cables, small parts	5 €
	Total	**87 €**

As a core, the prototype consists of a single-board microprocessor, a connector board for sensors and a sensor to measure PM2.5. These three main components will be described below.

<u>Microprocessor: Arduino Uno</u>

The Arduino is an open-source electronics platform based on easy-to-use hard- and software (Arduino.cc, 2017). Due to its simple and accessible user interface, the platform has been used by professionals and non-professionals in numerous interactive projects and applications. Arduino boards are capable of reading inputs and turning them into outputs, through the set of instructions that are sent to the microcontroller board. The Arduino IDE software uses the Arduino's C-based programming language to write, edit, compile and upload the developed codes to the interface board (Evans, 2011).

The Arduino Uno is based on the ATmega328P, ant its board consists of 14 digital input/output pins of which 6 can provide PWM output and 6 analog input pins (Figure 9). It also has a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. The microcontroller board can be powered through USB or the power jack using an AC-DC adapter or battery.

Figure 9: Arduino board

Connector Board: SenseBox-Shield

The SenseBox-Shield is a sensor connector board designed by the SenseBox Project. In contrast to existing connector boards available on the market, the SenseBox-Shield has different connectors for the diverse hardware interfaces provided by Arduino, and it can reduce the risk of connecting a module to the incorrect interface (Wirwahn, 2016). Moreover, it offers the possibility to store data on a MicroSD card and to provide a time stamp, which is controlled by the real-time clock (RTC), type RV8523, which has a low current consumption. A lithium battery ensures that time and date are maintained even when the device is switched off. The shield is simply plugged into the Arduino microcontroller board and can thus substitute its functionality (Pesch, 2015). An overview of the SenseBox-Shield is shown in Figure 10.

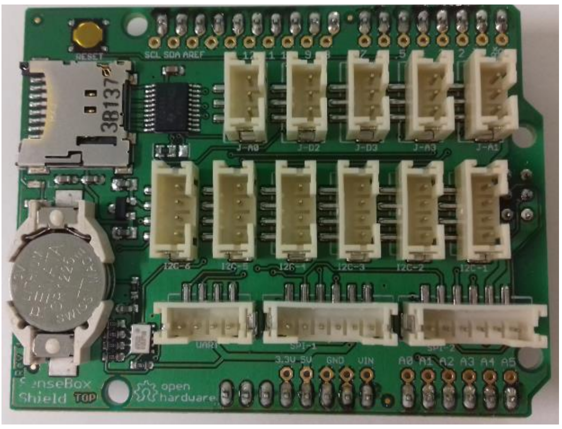

Figure 10: SenseBox-Shield

PM2.5 Sensor: Shinyei PPD42NS

The Shinyei PPD42NS consists of a light chamber in which a light-emitting diode (LED) shines a light on the particles, and the amount of light that is deflected by the particles is measured by a photodiode detector (light receptor). A resistive heater positioned at the bottom of the chamber helps to move air convectively from the bottom to the top outlet of the chamber (Austin et al., 2015).

Figure 11 illustrates the PM sensor operation, while Figure 12 presents the internal components of the sensor.

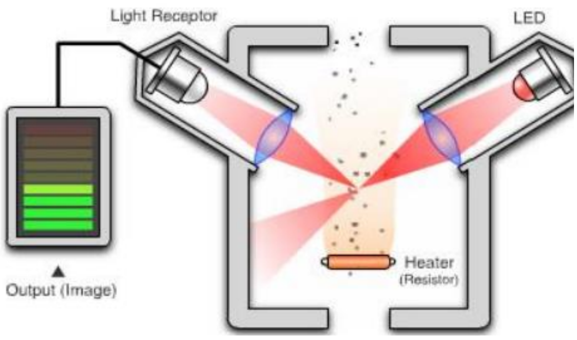

Figure 11: Schematic showing how the particle sensor operates (USEPA, 2015)

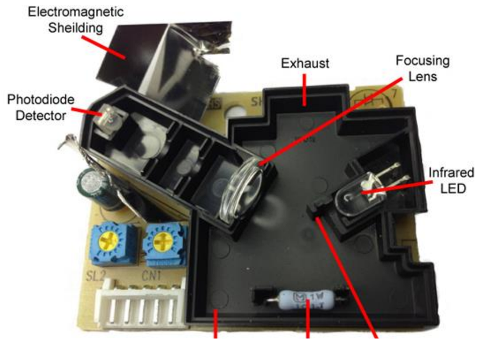

Figure 12: Inside the Shinyei PPD42NS

The signal processing is controlled by additional electronics, and the raw sensor output consists of low pulse occupancy (the amount of time particles are detected by the photodiode sensor), which is proportional to particle count concentration (Wang et al., 2015). The number of particles per 0.01 cubic foot can then be calculated by means of a function determined from the datasheet of the sensor (Pesch, 2015). By default, the fine particle matter concentration is not expressed in an absolute particle number per 0.01 cubic foot, but in a concentration of µg/m³. The conversion is then based on the assumption that the particles are spherical and have an average density of 1.65µg/m³ (Tittarelli et al., 2008).

The technical specifications of the sensor are presented in Table 9.

Table 9: Specifications of the Shinyei PPD42NS

Dimension W x H x D (mm)	59 x 45 x 22
Detectable PM size range	~1µm
Operation voltage	5 +- 0.5 V
Current consumption	<90 mA
Operation temperature	0 ~ 45°C
Operation humidity	<95%
Sensitivity	N/A
Output signal	Pulse width modulation

3.1.2 Prototype Operation

Figure 13 presents the steps for the operation of the prototype. Once all the components are installed, it is necessary to write a code to enable the board to collect and store the data. After being uploaded to the microcontroller, the code runs in a loop successively as long as the power supply of the microcontroller is not interrupted. In order to supply the device, the prototype is charged continuously from an external battery supplying 5V power.

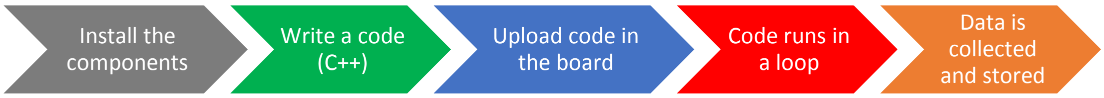

Figure 13: Prototype operation flow

The prototype can measure and record readings for PM2.5, temperature, and humidity, and store it on a microSD card in intervals of 15 seconds. The measured values are comma separated value files (CSV) and can be easily converted into a table of data. Each time the prototype starts to operate, it is checked if the microSD card is correctly connected. A section of a file is shown in Figure 14.

```
PM2.5,Time,Date, Temperature, Humidity
11.75,1:26:35,12.12.2016,27.04,41.24
9.65,1:26:50,12.12.2016,27.04,41.74
11.74,1:27:5,12.12.2016,27.07,41.45
10.90,1:27:20,12.12.2016,27.03,41.84
16.36,1:27:35,12.12.2016,27.00,41.82
14.31,1:27:50,12.12.2016,27.03,42.30
15.40,1:28:5,12.12.2016,27.01,42.30
15.80,1:28:20,12.12.2016,27.04,42.02
15.26,1:28:35,12.12.2016,27.04,42.33
16.54,1:28:50,12.12.2016,26.92,43.01
15.25,1:29:5,12.12.2016,27.05,43.76
```

Figure 14: Example of a log file of the prototype

3.1.3 Case Design

All the components were housed in a small and portable case, made of polycarbonate, and with the following dimensions: 18x8x6cm.

In order to ensure a good aeration of the box, the laterals were perforated, as can be seen in Figure 8. In one of the sides of the case, a small fan with a volumetric flow of 12.9m³/h was installed (SUNON, 2010). Thanks to the active ventilation, the sensors inside the case were always supplied with fresh air for analysis.

All the materials, coding, as well as pictures of the prototype, can be found on: https://github.com/janalodi/SenseBox-PM

3.2 EXPERIMENTS

Several field experiments were conducted in different environments and under different conditions.

Aiming to evaluate the performance of similar PM2.5 sensors purchased in the same and in different years, 3 prototypes were built. The Prototypes 1 and 2 contain particle sensors purchased in the same year (2015), while Prototype 3 uses the same sensor, but acquired in 2016.

To evaluate the performance of the prototypes, a pair of them was co-located alongside a reference instrument (DustTrak). A commercial low-cost device (AirBeam) was also tested in all the experiments.

3.2.1 Description of the Experiments

Table 10 summarizes the experiments, their location, type, and environment, as well as their objective and duration. The experiments occurred from 06/12/2016 to 12/12/2016.

Table 10: Summary of the experiments

Experiments	Local	Type	Environment	Objective	Duration	Instruments
1	House	Indoor	Normally occupied house and cooking	Measure large variations in the pollutant concentration	180 min	Prototype 1 Prototype 2 DustTrak AirBeam
2	House	Indoor	Normally occupied house and cooking	Measure large variations in the pollutant concentration	120 min	Prototype 1 Prototype 3 DustTrak AirBeam
3	House	Indoor	Normally occupied house and smoke of cigarettes	Measure large variations in the pollutant concentration	120 min	Prototype 1 Prototype 3 DustTrak AirBeam
4	University	Indoor	Entrance of the institute	Measure low concentration of pollutant	120 min	Prototype 1 Prototype 3 DustTrak AirBeam
5	Center of Münster	Outdoor	Christmas Market	Measure high concentration of pollutant	180 min	Prototype 1 Prototype 3 DustTrak AirBeam
6	Center of Münster	Outdoor	Christmas Market	Measure high concentration of pollutant	120 min	Prototype 1 Prototype 3 DustTrak AirBeam

The first three experiments had the main goal to analyze the performance of the prototype on measuring large variations of pollutant concentration. Cooking and smoking have been shown to lead to substantially elevated indoor concentrations (Wallace et al., 2011). Thus, a short series of controlled tests were performed in a residential environment.

The experiment 4 aimed to evaluate the performance in an environment with a potential low concentration of particles. It was conducted inside the building of the Institute for Geoinformatics.

The Experiments 5 and 6 were conducted in an outdoor environment, during the Christmas Market which occurred during the months of November and December in Münster. This environment is supposed to present a high concentration of particulate matter, due to a large number of people circulating in the area, as well as cigarette smoke and cooking activities.

Figure 15 presents one of the experiments conducted in this study. It is possible to see the pair of the prototypes connected to 2 external batteries, as well as the AirBeam connected to the smartphone and the DustTrak.

Figure 15: Example of one experiment

3.2.2 Instruments

More information about the reference monitor and the commercial low-cost instrument tested will be presented below.

3.2.2.1 Reference Monitor: DustTrak

The TSI DustTrak 8534 Handheld used in this study is a light-scattering laser photometer that simultaneously measures size-segregated mass fraction concentrations (PM1, PM2.5, Respirable, PM10, and Total PM fractions). It has a real-time display and can continuously log data at user-defined intervals. Data can then be exported and analyzed in the TrakPro™ software (TSI, 2014).The instrument is capable of running for up to 6 hours; it has a concentration range of 0.001 to 150 mg/m³ and a particle size range of 0.1 to 15µm. Table 11 presents the technical specifications of the instrument.

Table 11: Technical specifications: TSI DustTrak 8534 Handheld (TSI, 2014)

Sensor Type	90° light scattering
Particle Size Range	0.1 to 15 µm
Aerosol Concentration Range	0.001 to 150 mg/m³
Operational Temp	32 to 120°F (0 to 50°C)
Storage Temp	-4 to 140°F (-20 to 60°C)
Operational Humidity	0 to 95% RH, non-condensing
Time Constant	User adjustable, 1 to 60 seconds
Data Logging	5 MB of on-board memory
Log Interval	User adjustable, 1 second to 1 hour
Communications	USB (host and device). Stored data accessible using flash memory drive
Power–AC	Switching AC power adapter with universal line cord, 115–240 VAC

3.2.2.2 Commercial PM2.5 device: AirBeam

The AirBeam is an air quality monitor which also uses a light scattering method to measure fine particulate matter. In the device, air is drawn through a sensing compartment while light from a LED bulb scatters off particles present in the airstream. The light scattered is recorded by a detector which estimates the number of particles. The collected data is sent via Bluetooth to an application on a smartphone (AirCasting, 2017). The AirBeam has a rechargeable lithium battery, which can operate for up to 10 hours. Table 12 presents the technical specifications for the AirBeam.

Table 12: Technical specifications: AirBeam

Sensor Type	light scattering
Weight	7 ounces
Particle Sensor	Shinyei PPD60PV
Temperature & Relative Humidity Sensor	MaxDetect RH03
Bluetooth	Nova MDCS42, Version 2.1+EDR
Microcontroller	Atmel ATmega32U4
Bootloader	Arduino Leonardo
Time Constant	~ 1 second
Aerosol Concentration Range	1 to ~400µg/m³

3.3 ANALYTICAL METHODS

Below the methods applied to the data collected by the instruments will be described. Microsoft Excel was used for all data processing and analysis.

3.3.1 Data Treatment Methods

1) Data from all the instruments was time-matched;
2) Zero values were excluded from the database;
3) Data was aggregated in intervals of 1-minute, through the calculation of the mean, to facilitate the analysis of the results and also because the three instruments provide PM2.5 mass concentrations in different time resolutions (DustTrak and the AirBeam collected data in 1-second intervals, while the prototype in such of 15-seconds).

3.3.2 Assessment Methods

As described in section 2.2.1.2, at present there are no official criteria to evaluate air quality sensors. This study used the common practice methods found in the literature to assess the performance of the instruments utilized in this research.

1) Time-series graphs

Time-series graphs presenting the concentrations of PM2.5 over time were plotted for the instruments in all of the experiments. This type of graph is an important tool for displaying trends and changes in the data over time.

2) Correlation Analysis

To quantify and compare the strengths of the relations, correlation coefficients (R) and coefficients of determination (R^2) were calculated to each pairwise dataset.

R measures the strength and the direction of a linear relationship between two variables. The value of R is such that $-1 \leq R \leq +1$. The + and – signs are used for positive linear correlations and negative linear correlations, respectively.

R^2 gives the proportion of the variance (fluctuation) of one variable that is predictable from the other variable. It is a measure to determine how precise one can be in making predictions from a certain model/graph. The coefficient of determination is such that $0 \leq R^2 \leq 1$.

3) Data Completeness

The total of valid data achieved from a measurement system, compared to the total that was expected to be obtained under normal and correct conditions, is called data completeness (Williams et al., 2014). This value was calculated for each instrument for all the experiments.

4 RESULTS

The following chapter presents the results of the experiments conducted in this study. For each of the 6 experiments, the time series graphs and the statistical analysis of the instruments' performance will be presented. Then, the results for the data completeness will follow.

4.1. EXPERIMENT 1

Figure 16 presents the time series graphs for the Experiment 1. From the images, it is possible to notice that all instruments presented a substantial response to the high change of PM2.5-concentration, when the cooking was initiated approximately in minute 34. However, the concentration reported by DustTrak was consistently higher than the other instruments' measurements. Its highest value was almost 4000µg/m³ at the peak of the experiment; while AirBeam reported 180µg/m³ and the Prototypes 1 and 2 presented 55µg/m³ and 65µg/m³, respectively. The different aspects of the AirBeam's behavior will be further discussed in section 5.1.3.

Figure 16: Time series graphs for Experiment 1

Table 13 shows statistical summaries of linear correlation coefficients (R) and coefficients of determination (R^2) for all instruments. Analysing the first coefficient, a high linear correlation was found between the reference monitor (DustTrak) and Prototype 1 (R = 0.82), as well as between the Prototype 2 and DustTrak (R = 0.78). There was a high consistency between the Prototype 1 and Prototype 2 measurements (R = 0.96 and R^2 = 0.92). This result can suggest a good factory calibration of the

PPD42NS sensors purchased in the same year. The data displayed by DustTrak and AirBeam exhibited less congruence (R = 0.51 and R^2 = 0.26).

Table 13: Linear correlation (R) and coefficients of determination (R^2) for Experiment 1

	DustTrak		*AirBeam*		*Prototype 1*	
Experiment 1	*R*	*R2*	*R*	*R2*	*R*	*R2*
AirBeam	0.51	0.26	1	1		
Prototype 1	0.82	0.67	0.62	0.38	1	1
Prototype 2	0.78	0.61	0.60	0.36	0.96	0.92

4.2 EXPERIMENT 2

Figure 17 presents the time series data of DustTrak, AirBeam and Prototypes 1 and 3 in Experiment 2. From the graphs, it is possible to observe that all the devices showed an evident response to the high variation of pollutant concentration and presented two peaks, although the time series presented different behaviors. A similar trend is detectable mainly for DustTrak and Prototype 1, which will be statistically confirmed by the high linear correlation (R = 0.88). In this experiment, the correlation between AirBeam and Prototype 3 was also good (R = 0.74). The other instruments' measurements showed less correspondence, as can be seen in Table 14.

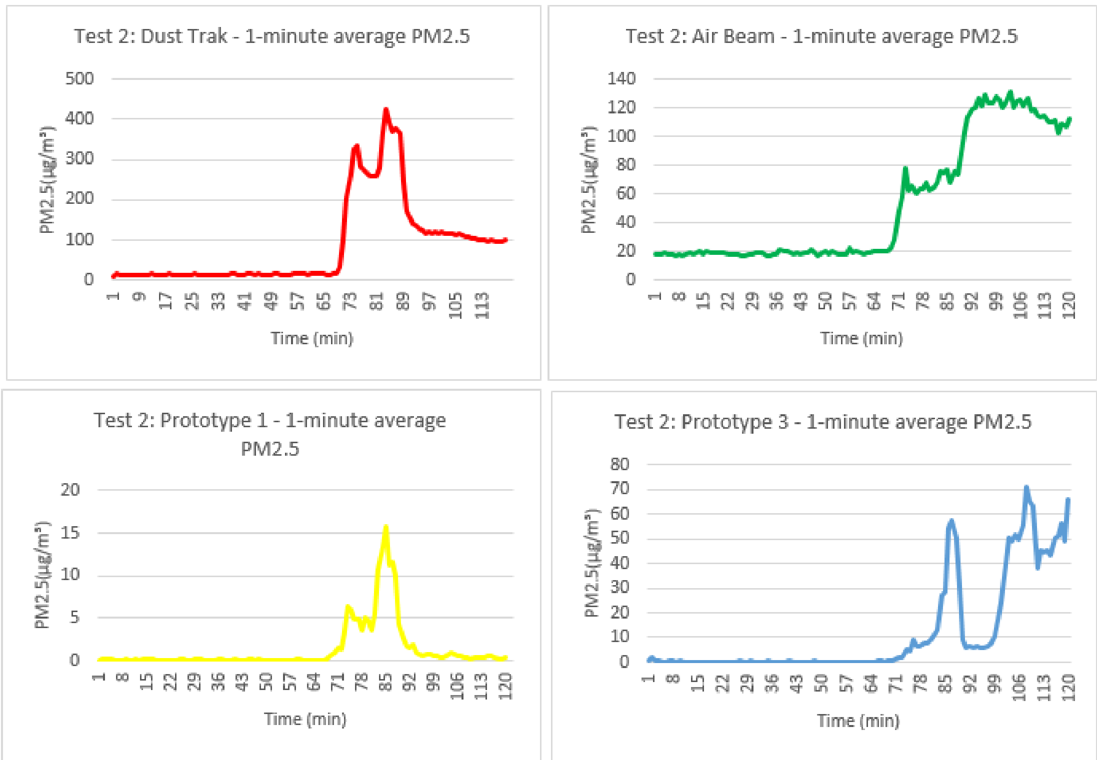

Figure 17: Time series graphs for Experiment 2

Table 14: Linear correlation (R) and coefficients of determination (R^2) for Experiment 2

	DustTrak		*AirBeam*		*Prototype 1*	
Experiment 2	*R*	*R2*	*R*	*R2*	*R*	*R2*
AirBeam	0.54	0.29	1	1		
Prototype 1	0.88	0.77	0.13	0.02	1	1
Prototype 3	0.42	0.18	0.74	0.55	0.19	0.04

4.3 EXPERIMENT 3

Figure 18 illustrates the time series plots for Experiment 3, testing the effect of cigarette smoke. From the figure, the rapid increase of PM2.5-concentration can be observed, as well as a similar behaviour between DustTrak and Prototype 3 graphs. Their visual agreement is statistically verifiable in Table 15, where a strong coefficient of determination was found between the instruments ($R^2 = 0.85$).

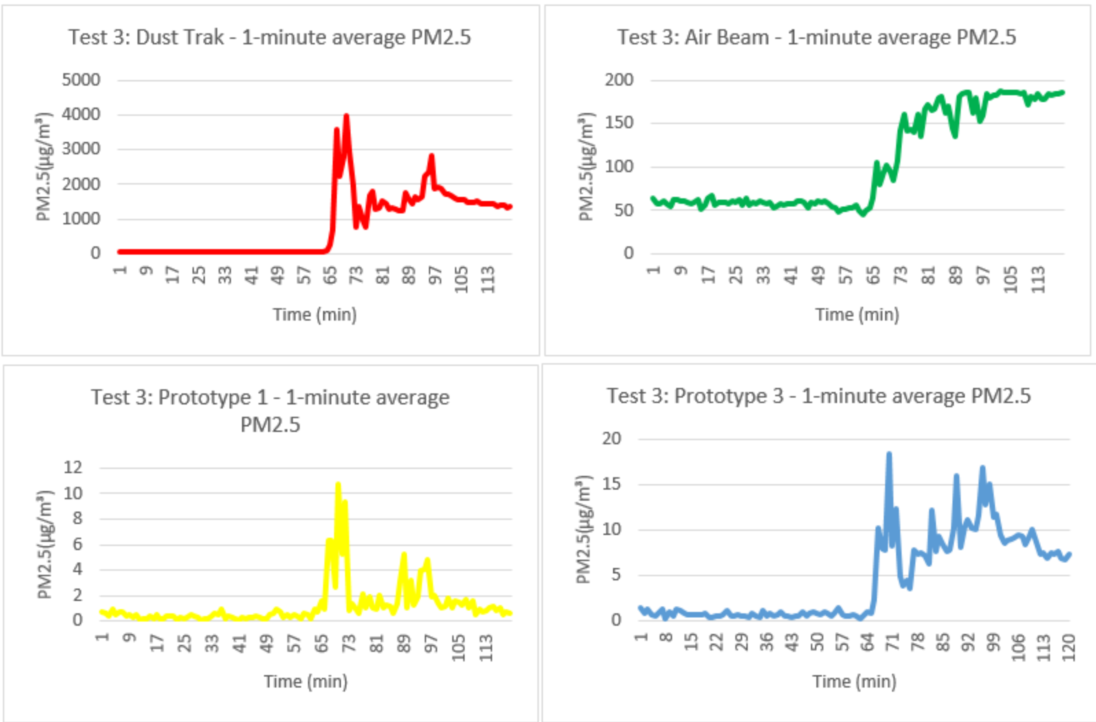

Figure 18: Time-series graphs for Experiment 3

A moderate to good agreement was revealed between the reference instrument and AirBeam and Prototype 3 ($R = 0.74$-0.75 and $R^2 = 0.55$-0.56), as well as between the Prototype 3 and AirBeam ($R = 0.83$ and $R^2 = 0.69$).

Table 15: Linear correlation (R) and coefficients of determination (R^2) for Experiment 3

	DustTrak		*AirBeam*		*Prototype 1*	
Experiment 3	*R*	*R2*	*R*	*R2*	*R*	*R2*
AirBeam	0.75	0.56	1	1		
Prototype 1	0.74	0.55	0.25	0.06	1	1
Prototype 3	0.92	0.85	0.83	0.69	0.67	0.45

4.4 EXPERIMENT 4

Figure 19 presents the results of the experiment conducted at the university. Visually, it is recognizable that DustTrak and AirBeam performed very similar, which can be statistically verified by the analysis of agreement. ($R = 0.93$ and $R^2 = 0.86$). The other instruments presented very low agreement, as illustrated in Table 16.

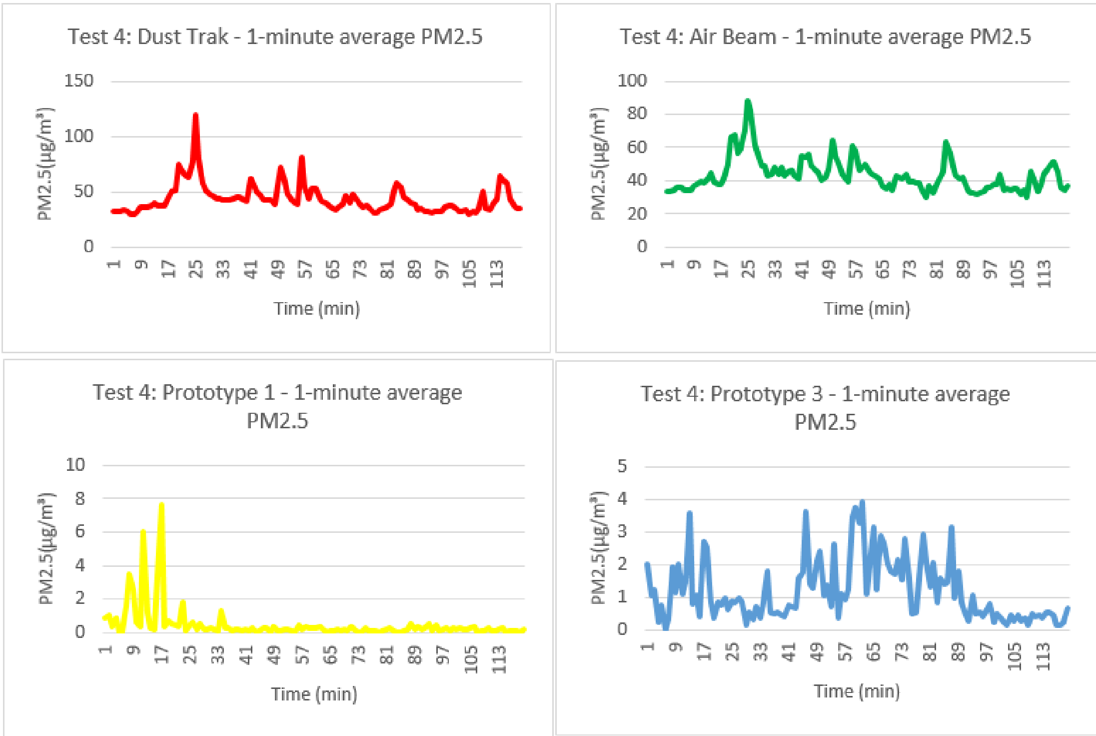

Figure 19: Time series graphs for Experiment 4

Table 16: Linear correlation (R) and coefficients of determination (R^2) for Experiment 4

	DustTrak		*AirBeam*		*Prototype 1*	
Experiment 4	*R*	*R2*	*R*	*R2*	*R*	*R2*
AirBeam	0.93	0.86	1	1		
Prototype 1	-0.04	0	-0.07	0	1	1
Prototype 3	0.01	0	0	0	0.12	0.01

4.5 EXPERIMENT 5

Figure 20 shows the performance of the instruments in the first experiment in the Christmas Market. AirBeam and DustTrak presented a moderate linear correlation and a moderate coefficient of determination (R = 0.66 and R^2 = 0.44). All the other instruments presented a very weak pairwise agreement (Table 17).

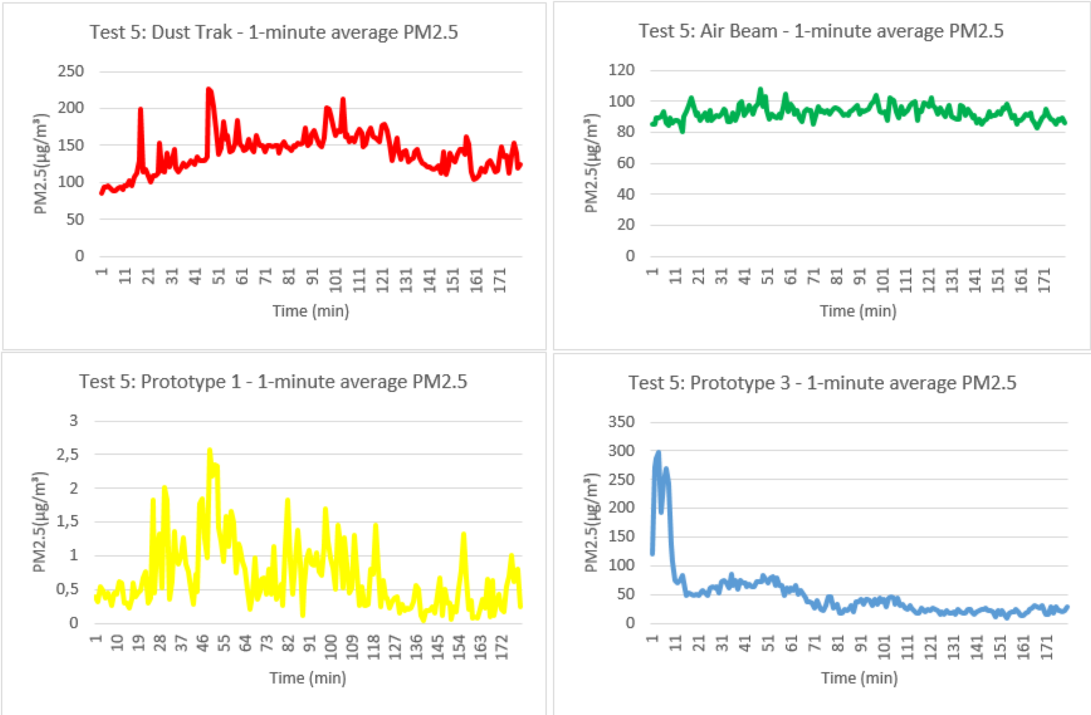

Figure 20: Time series graphs for Experiment 5

Table 17: Linear correlation (R) and coefficients of determination (R^2) for Experiment 5

	DustTrak		*AirBeam*		*Prototype 1*	
Experiment 5	*R*	*R2*	*R*	*R2*	*R*	*R2*
AirBeam	0.66	0.44	1	1		
Prototype 1	0.32	0.10	0.25	0.06	1	1
Prototype 3	-0.37	0.14	-0.18	0.03	0.09	0.01

4.6 EXPERIMENT 6

Figure 21 presents the response of the instruments in Experiment 6, also conducted at the Christmas Market. AirBeam presented a good linear correlation (0.75) and a moderate coefficient of the determination with DustTrak (0.56), while the other instruments presented a very low correlation (Table 18).

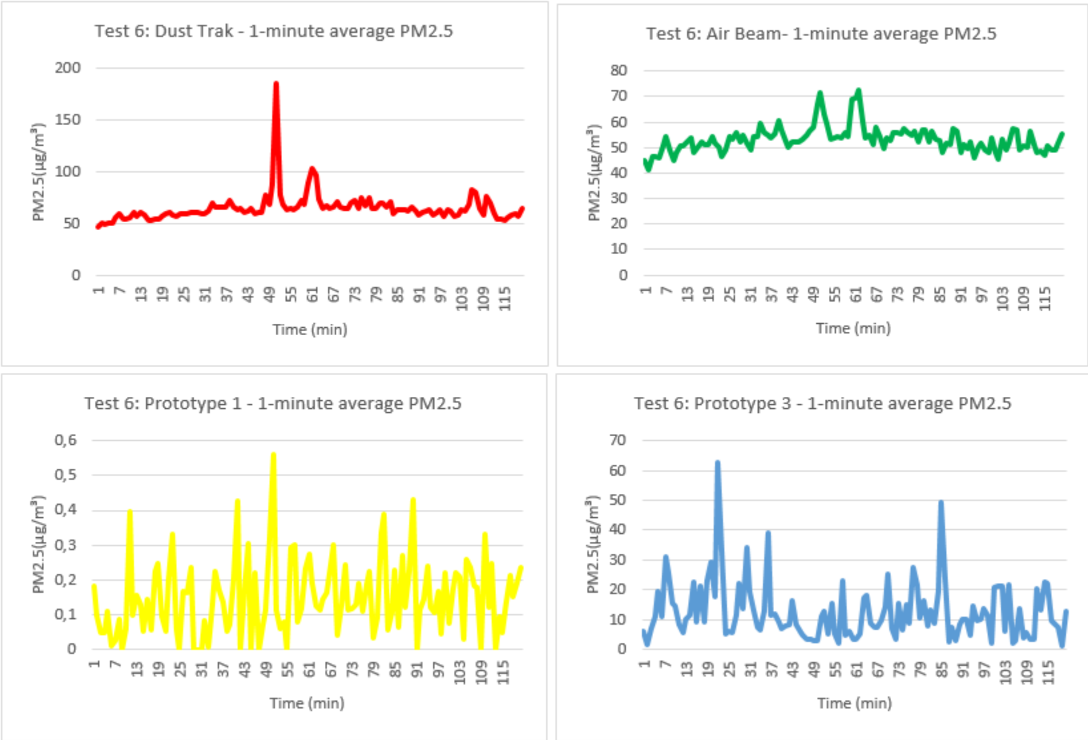

Figure 21: Time series graphs for Experiment 6

Table 18: Linear correlation (R) and coefficients of determination (R^2) for Experiment 6

	DustTrak		*AirBeam*		*Prototype 1*	
Experiment 6	*R*	*R2*	*R*	*R2*	*R*	*R2*
AirBeam	0.75	0.56	1	1		
Prototype 1	0.24	0.06	0.21	0.04	1	1
Prototype 3	-0.16	0.03	-0.20	0.04	-0.09	0.01

4.7 DATA COMPLETENESS

Table 19 presents the results of data completeness for all the instruments in each experiment. The last column shows the weighted arithmetic mean for all the experiments, based on the duration of the tests.

Table 19: Data Completeness Analysis

	Exp 1	**Exp 2**	**Exp 3**	**Exp 4**	**Exp 5**	**Exp 6**	**All**
Sensor 1	90%	53%	89%	55%	90%	48%	74%
Sensor 2	83%	-	-	-	-	-	83%
Sensor 3	-	82%	99%	93%	100%	100%	95%
AirBeam	86%	86%	86%	86%	86%	86%	86%
DustTrak	100%	100%	100%	100%	100%	100%	100%

5 DISCUSSION

This chapter focuses on the central aspects arisen in this study. The main findings and limitations are discussed in the next sections.

5.1 MAIN FINDINGS

5.1.1 Performance of the Prototypes

The main objective of this research was to analyze the performance of low-cost prototypes on measuring PM2.5 through comparison with a reference instrument. On account of this, the statistical agreements between the prototypes and the reference monitor are summarized in Table 20. It can be observed that the prototypes had a variable agreement with DustTrak in the different experiments.

Table 20: Summary of the agreement of the prototypes with DustTrak

	TEST 1		*TEST 2*		*TEST 3*		*TEST 4*		*TEST 5*		*TEST 6*	
	R	***R2***	***R***	***R2***	***R***	***R2***	***R***	***R2***	***R***	***R2***	***R***	***R2***
Prototype 1	0.82	0.67	0.88	0.77	0.74	0.55	0	0	0.32	0.10	0.24	0.06
Prototype 2	0.78	0.61										
Prototype 3			0.42	0.18	0.92	0.85	0	0	-0.37	0.14	-0.16	0.03

The response of the prototypes in the experiments of cooking and cigarette smoke (Experiments 1, 2 and 3) were moderate to very correlated to the reference instrument (R = 0.74-0.92 and R^2 = 0.55-0.85), with exception of the Prototype 3 in Experiment 2. These results suggest that the PPD42 sensor responds well in environments with high variability of particle-concentration, mainly with a creation of particles. These findings are consistent with a previous study by Wang (Wang et al., 2015), which examined the performance of 3 different low-cost sensors in a laboratory, including the one used in this study. In the referred study, particles were created by burning incense, and a very high agreement (R^2 = 0.95) between the instruments was registered.

A previous study in the US testing another low-cost sensor (Sharp's Optical Dust) observed similar results in similar experiments (Olivares et al., 2012). In that study, a prototype was installed in a house and its performance was evaluated during residential activities. The results of the study also demonstrated that in these indoor environments, low-cost sensors may be useful; the prototypes responded clearly to activities like cooking and smoking of cigarettes, being capable of presenting the main trends with a good temporal resolution. In addition, another important source of indoor exposure to PM2.5 is biomass burning, where studies reported that mean daytime concentration of PM2.5 in homes using wood as fuel was nearly 3000µg/m3 (Siddiqui et al., 2009). In this sense, these sensors could be also useful in monitoring biomass cooking and/or heating events (Austin et al., 2015).

However, the performance of the prototypes developed in this study was very weak in environments with lower variations of the particle-concentration (disparities smaller than 100µg/m³, approximately), for both environments, inside the institute, and at the Christmas Market. A previous study by the Community Air Sensor Network from EPA presented consistency with these results. In the referenced study, a network of several selected sensors was tested in multiple locations for a long-term deployment, for7 months (Jiao et al., 2016). The three collocated Air Quality Egg units, which also use PPD42NS sensors, revealed poor correlation (R = 0.06-0.40) with the Federal Equivalent Method (FEM). In another study, the same particle sensors presented a nonlinear response at very high concentrations (hourly average PM2.5 ranging 77-889µg/m3) and authors used high-order models to correct their data (Gao et al., 2015).

Nevertheless, other studies presented different results, e.g. the same sensors deployed in an environment with low to moderate PM2.5 concentrations (PM2.5 ranging 3-20µg/m³) revealed a good correlation with a reference monitor (R = 0.72 for 24h averages) (Holstius et al., 2014).

5.1.2 Comparison of Identical Sensors

An additional objective of this research was to compare the performance of identical sensors purchased in the same year and in different years. The results revealed that the performance agreement between the Prototypes 1 and 2, which were acquired in the same year, was very high ($R^2 = 0.92$). However, the Prototypes 1 and 3, both bought in different years, presented no correlation in any of the experiments, with exception of the smoking experiment (Test 3), which revealed a moderate linear correlation between these prototypes (R = 0.67).

In the laboratory study conducted by Wang (Wang et al., 2015), the performance of the same sensor was equivalent to the first experiment of this study, revealing a high correlation between the performance of identical sensors ($R^2 = 0.95$). Nevertheless, in the field study conducted by the EPA (Jiao et al., 2016), a comparison of identical sensors displayed a moderate agreement (R= 0.55). In a laboratory study with 20 identical sensors, Austin (Austin et al., 2015) evaluated that the response of these sensors to produced aerosol atmospheres is idiomatic, implicating that each sensor follows its own response curve.

Therefore, this study agrees with other studies to the extent that, before being used in commercialized particle monitors, each sensor requires individual calibration, since these existing systematic errors may considerably affect the measurements carried out by the sensors.

5.1.3 AirBeam Performance

An additional goal of the current research was to evaluate the performance of a commercial low-cost PM2.5 device. For that reason, Table 21 summarizes the agreement analysis of AirBeam with DustTrak.

Table 21: Summary of the agreement of AirBeam with DustTrak

	TEST 1		*TEST 2*		*TEST 3*		*TEST 4*		*TEST 5*		*TEST 6*	
	R	***R2***	***R***	***R2***	***R***	***R2***	***R***	***R2***	***R***	***R2***	***R***	***R2***
AIRBEAM	0.51	0.26	0.54	0.29	0.75	0.56	0.93	0.86	0.66	0.44	0.75	0.56

The device revealed a strong correlation with the reference monitor in the experiment conducted in the institute (R = 0.93) and a good correlation in the cigarette smoke experiment and in the ones performed at the Christmas Market (R = 0.66-0.75). However, in the cooking tests (Experiments 1 and 2), the agreement with the reference monitor was lower (R = 0.51-0.54 and R^2 = 0.26-0.29).

On the website of the manufacturer (AirCasting, 2016), there is a study conducted in the US, in which AirBeam units were evaluated in comparison with a reference monitor (Thermo Scientific pDR-1500). In the study, experiments were conducted in ambient air below 100µg/m³, and also during indoor cardboard burning, and both tests resulted showing a strong linear relationship between AirBeam and the reference instrument (R^2 > 0.94). However, the measurements became increasingly non-linear on concentrations above 100µg/m³, and the author affirms that the performance of the device decreases as PM2.5-concentration increases. In another experiment, when compared to a Teflon filter subjected to gravimetric analysis, the correlation was lower (R^2 = 0.70).

In a study by the EPA, three AirBeam units were also evaluated in a long-term experiment. The results showed that the devices presented a moderate agreement (R = 0.65-0.66) (Jiao et al., 2016).

It is important to mention that, besides the study described on the website of the manufacturer, only 1 study was found which evaluates the performance of the AirBeam. The manufacturer himself says that additional research is required to fully characterize the performance of the AirBeam; hence, studies as the one conducted in this research are highly necessary.

Limit of detection

In terms of the limit of detection, the manufacturer informs on his website that AirBeam's maximum limit of detection is approximately 400µg/m³. However, in all of the experiments conducted in this research, the device couldn't record measurements above 180µg/m³. Figure 22 can illustrate this issue more evidently, presenting the time series in Experiment 3, without averaging to facilitate this analysis. It is evident that there is a limit in the capability of the sensor on measuring a concentration exceeding

180µg/m³. This limitation suggests a potential reason for the decrease in the performance of the device in environments with particle-concentration above this value.

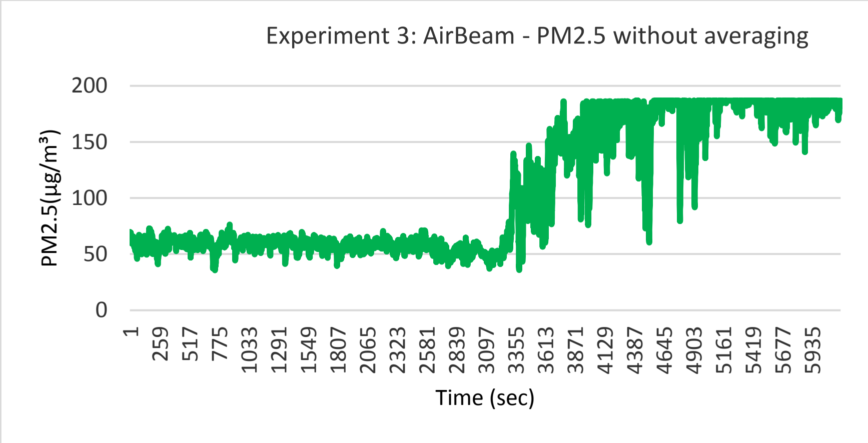

Figure 22: AirBeam time series without averaging in Experiment 3.

Reducing the scale of the graph to a value near the limit of detection of the AirBeam found in this study, Figure 23 presents the time series graph plotted to the Experiment 1 to AirBeam and DustTrak. It can be noticed that, although the device could not record the high values found by the DustTrak (near 4000µg/m³ in this experiment), it was capable of indicating well the main trends of PM2.5 concentration, showing a first peak followed by a smooth decrease after the cooker had been halted.

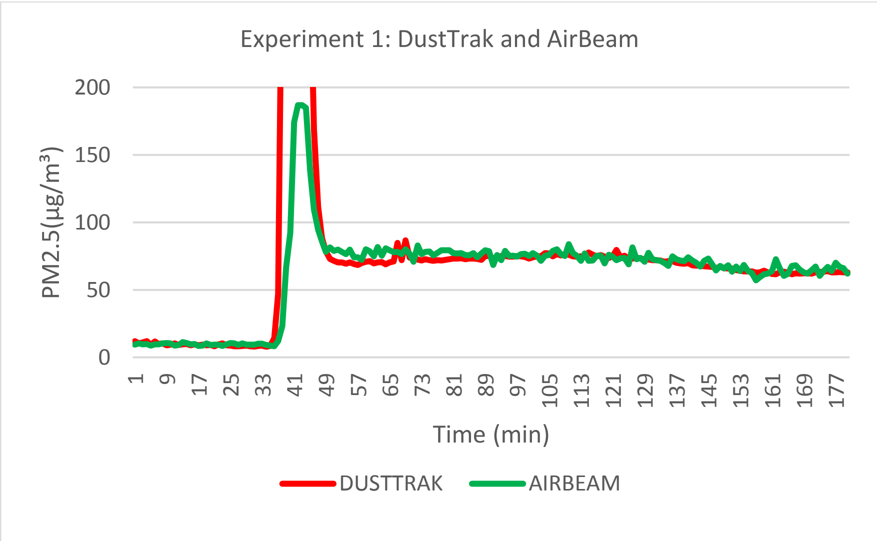

Figure 23: AirBeam and DustTrak time series in Experiment 1

5.1.4 Analysis of the Data considering the EU Directive and the EPA

Currently, there is no clear defined or universally accepted criterion to assess the performance of low-cost air quality sensors, as discussed in Chapter 3. Therefore, in this study, the performance of the sensors was evaluated based on their agreement, or lack thereof, with a reference monitor, using commonly associated descriptors for the strength of agreement (e.g., “weak/ moderate/ strong”).

For further classification of the performance, this section will evaluate the results considering the quality goals for indicative measurements outlined in the European Directive for Air Quality (UE, 2008) and also based on the suggested performance goals by the Air Sensor Guidebook from the EPA (Williams et al., 2014).

Assuming that the coefficient of determination is an indicator of precision, the 3 prototypes developed in this study had as average a precision of 41%, considering their performance in all of the 6 experiments. Following the same process of analysis, the AirBeam had a precision of 50%.

Considering the maximum uncertainty allowable for supplemental instruments in the EU Directive for particulate matter measurements (50%), the AirBeam presented the minimum value required for this application, thus, the device could be designated to supplement fixed measurements in the regulatory process. Nevertheless, the prototypes would not fulfill the EU performance-requirements for indicative measurements.

Considering the suggested performance goals by the EPA on the other hand, the AirBeam presented the minimum precision indicated to be used in “Education and Information” applications (precision > 50%). In these applications, exhibiting the existence of pollutants in some wide range of concentration predominates the importance of errorless measuring. For the other application areas, it would not be indicated to use any of the instruments. The prototypes, however, would not be indicated for any area of application, based on their low precision levels.

5.1.5 Data Completeness Analysis

In a weighted average, the Prototype 1 obtained 74% of completeness in the produced data. The Prototype 2 had 83% of valid data and the Prototype 3 presented a higher data completeness, 95%. The AirBeam generated the same amount of data in all the experiments, 86%. As the instrument measures the particle-concentration at a frequency of almost once a second, there are always missing values in the dataset. As expected, DustTrak produced 100% of the measurements in all the experiments.

The lower data completeness of the prototypes can be explained by the fact that the Shinyei sensor PPD42NS generated several zero values in its measurements, as has already been reported in previous studies (Holstius, 2016; Tan, 2016), i.e., even when there is known air pollution, the sensor reads zero.

According to the European Directive (EU, 2008), the criteria used for checking validity when aggregating data and calculating statistical parameters is 75% of valid data for one-hour measurements.

Assuming these values as criteria to analyse the data produced in this study, all the instruments would accomplish the minimum value defined by the directive to supplement fixed measurements, with exception of Prototype 1, which presented a slightly lower value for the data completeness (74%).

Considering the suggested performance goals for the data completeness by the EPA for the following areas of application: Education and Information (>50%), Hotspot Identification and Characterization (≥ 75%), Supplemental Monitoring (≥ 80%), Personal Exposure (≥ 80%), and Regulatory Monitoring (≥ 75%);the Prototypes 2 and 3 and the AirBeam would fulfill the minimum requirements indicated in all the 5 areas of applications, while Prototype 1 would be indicated only for education and information applications, based on its average performance (74%).

According to a study by the EPA (Williams et al., 2014), there are some common reasons for reductions in data completeness, specifically: data storage problems; data transmission errors; power loss and the required time for the consequent restart; the need for frequent or long-duration calibrations; and the time the device is offline for reparation.

5.2 LIMITATIONS

5.2.1 Monitor Reference

It is well-known that the most efficient method to analyze the performance of a sensor is the data comparison with official governmental air quality stations, which commonly utilize filter-based gravimetric samplers to measure PM2.5 and PM10, and are undergo rigorous quality control procedures (AQEG, 2005). However, the 2 official stations in Münster do not monitor fine particulate matter, only PM10 (LANUV, 2017). Due to this restriction, this study uses the DustTrak as the reference monitor for the analysis of performance.

Another potential limitation is related to the precision of the DustTrak measurements. Some studies reported that the DustTrak provides precise measurements of PM2.5, but occasionally its measurements are subject to biases (Ramachandran et al., 2011). The referred study suggests that the instrument response may be biased higher than the true value when mass median diameters are less than 2 mm, and be biased lower when mass median diameters are larger. Thus, the DustTrak measurements in this study possibly present some biased values that were not evaluated in this research. Either way, the DustTrak monitor was recently calibrated by its manufacturer (October 2016), thus, it is expected that it efficiently measures and records the pollutant-concentration.

A final limitation regarding the reference monitor is that all instruments utilized in this study detected particles via a light-scattering method. No sensors directly measured particle-mass nor possessed tools to prevent large particles from entering the optical cell.

5.2.2 Data Limitations

There are some technical aspects that can lead to a decrease in the performance of the low-cost sensors utilized in this study. The first of them are the different frequency of measurements and/or log intervals carried out by the instruments, much higher than the frequency of the PPD42NS sensor (1 measurement per 15 seconds). The AirBeam is capable of recording the measurements approximately once per second, while the log interval for the DustTrak is user adjustable, and it was defined as 1 second. Though 1-minute averaging is a method that facilitates the analysis, it can hide some important information.

Besides that, the instruments have different measurement units, AirBeam and DustTrak measure the fine particulate matter in µg/m³, while the raw unit for the PPD42NS sensor is low pulse occupancy, as explained in the session 3.1. During the conversion process, several assumptions are made, which can certainly reduce the performance of the sensors.

Moreover, a variety of factors which were not examined in this study can contribute to reducing the sensor performance of measuring air pollution trends. These aspects include the design of the device's case and adding ancillary sensors that can interfere with the sensor operation (e.g., temperature sensors) (Jiao et al., 2016). In addition, the pollution mixture and environmental conditions, such as wind, temperature and humidity, may also have an impact on the sensor's performance. The prototypes developed in this research also collect temperature and humidity values, but due to the short time, it was not possible to analyze the influence of those atmospheric conditions on the performance of the prototypes, thus remaining an important issue for future work.

6 CONCLUSION AND FUTURE WORK

Emerging air sensor technology is of widespread interest in the air pollution issue, a problem which continues to rise at an alarming rate worldwide and is unquestionably a public health emergency (World-Health-Organization, 2016). Low-cost sensors are a potential key to increasing the spatial resolution of air quality data sets and empower communities to measure air quality in their local environments (Jiao et al., 2016).

Recent advancements in low-cost air quality sensors are providing an inspiring opportunity for people to use this technology for a range of applications beyond traditional regulatory monitoring. However, low-cost air pollution sensors are still at an early stage of technology development, and several sensors are still in the phase of evaluation to determine the accuracy of their measurements (Williams et al., 2014).

The main goal of this research was to design and evaluate the performance of low-cost prototypes to measure PM2.5 in a series of field experiments. As a main result, the prototypes presented a good performance in environments with a high variation of particle concentrations (variations above 100µg/m^3), such as cooking-environments and exposure to cigarette smoke, for most of the experiments. Nonetheless, the prototypes obtained poor agreement in environments without high variability of particle concentrations. These findings suggest that caution must be exercised in presuming that measurements by low-cost sensors are representative of PM2.5.

The performance comparison between identical sensors acquired in the same year revealed a very high agreement ($R^2 = 0.92$). However, the prototypes which utilized sensors purchased in different years presented very weak correlation in most of the experiments. Therefore, this analysis demonstrates the necessity for individual sensor performance testing prior to field use, as confirmed by other studies.

The analysis of the AirBeam performance revealed a moderate to strong linear correlation ($R = 0.51$-0.93) with the reference monitor in all the experiments. This study also demonstrates that the AirBeam's maximum limit of detection is approximately 180µg/m^3, in contrast to the value of 400µg/m^{3}given by the manufacturer.

For applications of real-time measurements, the prototypes developed in this research may be especially utilized as indicative of PM2.5 hotspots and trends in ambient conditions, primarily in residences, monitoring the frequency and duration of high exposure events, such as cooking, smoking, and biomass burning. According to Holstius (Holstius et al., 2014), these less expensive and more portable devices may also facilitate rapid responses to accidental or natural releases of observed aerosols, as well as support more efficient public campaigns for urban "hot spots", with follow-up measurements completed with reference instruments.

Furthermore, the low-cost sensors may serve as preliminary indicators of pollution in many developing countries, where the PM concentrations in the atmosphere are recurrently high, and the commonly used accurate and traditional instruments are unaffordable.

FUTURE WORK

As a future work, different aspects of the sensors can be included in the assessment, such as the response time, the limit of detection and concentration resolution of the sensors. Furthermore, assess the performance of the devices near official air quality stations in future field studies is highly advised. Besides that, continuing work with more sensors under varying environmental and experimental conditions is essential to more precisely characterize the influence of atmospheric and operating conditions on their performance.

Apart from the technical analysis of the prototypes, an ongoing part of this study and future work is the evaluation of usability aspects of online platforms for air quality data visualization. A usability plan was already prepared with the help of a usability specialist in order to assess the effectiveness and efficiency of the usability of several platforms. In the usability plan, it was assumed that, in the best scenario, the platforms should allow the customers to: identify the environmental parameters the dispositive is able to measure; identify the number of devices located in a specific country/region; find the measurements produced by a specific device; visualize the historic of the data measured by each device; and download the data. The plan aims to provide recommendations for the existing and for future low-cost sensors projects.

Finally, despite their limitations, trends in the development of less expensive air quality monitoring technologies are likely to continue (Holstius et al., 2014). However, the impact of the propagation of low-cost air quality devices on the decision-making processes and on the whole system of air quality management still remains an open question.

BIBLIOGRAPHIC REFERENCES

Air Quality Egg. (2017). Air Quality Egg community-led sensing network.

AirCasting. (2016). Takingspace: The HabitatMap & AirCasting Blog. Retrieved January 15, 2017, from http://www.takingspace.org/

AirCasting. (2017). Air Casting. Retrieved December 10, 2016, from http://aircasting.org/

AQEG. (2005). Particulate Matter in the United Kingdom. *Defra, London*, 23.

Arduino.cc. (2017). Genuino Uno. Retrieved from https://www.arduino.cc/en/Main/arduinoBoardUno

Austin, E., Novosselov, I., Seto, E., & Yost, M. G. (2015). Laboratory evaluation of the Shinyei PPD42NS low-cost particulate matter sensor. *PLoS ONE*, *10*(9), 1–17. https://doi.org/10.1371/journal.pone.0137789

Bartonova, A., Lazovic, I., Jova, M., & Pokri, B. (2015). On the use of small and cheaper sensors and devices for indicative citizen-based monitoring of respirable particulate ..., (September). https://doi.org/10.1016/j.envpol.2015.08.035

Bonney, R., Shirk, J. L., Phillips, T. B., Wiggins, A., Ballard, H. L., Miller-Rushing, A. J., & Parrish, J. K. (2014). Citizen science: Next steps for citizen science. *Science*, *343*(6178), 1436–1437. https://doi.org/10.1126/science.1251554

Burke, J., Estrin, D., Hansen, M., Ramanathan, N., Reddy, S., & Srivastava, M. B. (2006). Participatory sensing. *In: Workshop on World-Sensor-Web (WSW'06): Mobile Device Centric Sensor Networks and Applications*, 117–134. https://doi.org/10.1109/MIC.2010.12

Devarakonda, S., Sevusu, P., Liu, H., Liu, R., Iftode, L., & Nath, B. (2013). Real-time air quality monitoring through mobile sensing in metropolitan areas. *2nd ACM SIGKDD International Workshop on Urban Computing - UrbComp '13*, 1. https://doi.org/10.1145/2505821.2505834

EPA. (2016). Criteria Air Pollutants. Retrieved December 12, 2016, from https://www.epa.gov/criteria-air-pollutants

EU. (2008). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Official Journal of the European Communities*, *152*, 1–43. https://doi.org/http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF

Evans, B. (2011). *Beginning Arduino Programming*. Apress. Retrieved from www.apress.com

"FabLab Barcelona." (2017). SmartCitizen. Retrieved November 25, 2016, from https://smartcitizen.me/

Gao, M., Cao, J., & Seto, E. (2015). A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of PM2.5 in Xi'an, China. *Environmental Pollution*, *199*, 56–65. https://doi.org/10.1016/j.envpol.2015.01.013

Goodchild, M. (2006). Citizens As Sensors: the World of Volunteered Geography. *Sciencex2.Org*, 1–15. Retrieved from http://sciencex2.org/files/Goodchild_VGI2007.pdf

Holstius, D. (2016). David Holstius: Code and comment on environmental health science. Retrieved November 24, 2016, from http://www.davidholstius.com

Holstius, D. M., Pillarisetti, A., Smith, K. R., & Seto, E. (2014). Field calibrations of a low-cost aerosol sensor at a regulatory monitoring site in California. *Atmospheric Measurement Techniques*, *7*(4), 1121–1131. https://doi.org/10.5194/amt-7-1121-2014

Jiao, W., Hagler, G., Williams, R., Sharpe, R., Brown, R., Garver, D., … Buckley, K. (2016). Community Air Sensor Network (CAIRSENSE) project: Evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. *Atmospheric Measurement Techniques*, *9*(11), 5281–5292. https://doi.org/10.5194/amt-9-5281-2016

LANUV. (2017). Landesanstalt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen. LANUV:Aktuelle Lufqualität. Retrieved December 10, 2016, from https://www.lanuv.nrw.de/luft/immissionen/aktluftqual/eu_luft_akt/

Levy, I. (2014). On the feasibility of measuring urban air pollution by wireless distributed sensor networks sensor networks. *Science of the Total Environment, The*, *502*(October). https://doi.org/10.1016/j.scitotenv.2014.09.059

Murugesan, S. (2007). Understanding Web 2.0. *IT Professional*, *9*(August), 34–41. https://doi.org/10.1109/MITP.2007.78

Neophytou, M., Sabatino, S. Di, Norford, L. K., Kumar, P., Morawska, L., Martani, C., … Britter, R. (2015). The rise of low-cost sensing for managing air pollution in cities. *Environment International*, *75*(February). https://doi.org/10.1016/j.envint.2014.11.019

Olivares, G., Longley, I., & Coulson, G. (2012). Development of a low-cost device for observing indoor particle levels associated with source activities in the home. *22nd Annual Meeting of the International Society of Exposure Science*, (January 2017), 1–6. Retrieved from http://www.researchgate.net/publication/229575639_Development_of_a_low-cost_device_for_observing_indoor_particle_levels_associated_with_source_activities_in_the_home/file/d912f500f82b73b308.pdf

Paprotny, I., Doering, F., Solomon, P. A., White, R. M., & Gundel, L. A. (2013). Sensors and Actuators A : Physical Microfabricated air-microfluidic sensor for personal monitoring of airborne particulate matter : Design , fabrication , and experimental results ☆. *Sensors & Actuators: A. Physical*, *201*, 506–516. https://doi.org/10.1016/j.sna.2012.12.026

Pesch, M., Bartoschek, T., & Malkus, A. (2015). SenseBox : Airquality - Entwicklung einer Low-Cost Lu qualitätsmessstation auf Basis der SenseBox Zusammenfassung.

Ramachandran, G., Adgate, J. L., Hill, N., Sexton, K., Pratt, G. C., Bock, D., … Bock, D. (2011). Comparison of Short-Term Variations (15- Minute Averages) in Outdoor and Indoor PM 2 . 5 Concentrations Comparison of Short-Term Variations (15-Minute Averages) in Outdoor and Indoor PM 2 . 5 Concentrations, *2247*(January 2017). https://doi.org/10.1080/10473289.2000.10464160

SCAQ. (2017). South Coast Air Quality Management District.

SenseBox. (2017). SenseBox | Die Kiste mit Sinn. Retrieved January 24, 2017, from http://sensebox.uni-muenster.de/

Siddiqui, A. R., Lee, K., Bennett, D., Yang, X., Brown, K. H., Bhutta, Z. A., & Gold, E. B. (2009). Indoor carbon monoxide and PM 2.5 concentrations by cooking fuels in Pakistan. *Indoor Air*, *19*, 75–82. https://doi.org/10.1111/j.1600-0668.2008.00563.x

Sivaraman, V., Carrapetta, J., Hu, K., & Luxan, B. G. (2013). HazeWatch: A participatory sensor system for monitoring air pollution in Sydney. *38th Annual IEEE Conference on Local Computer Networks - Workshops*, 56–64. https://doi.org/10.1109/LCNW.2013.6758498

SUNON. (2010). FAN-4010 5V DATASHEET.

Tan, D. (2016). irq5.io: adventures of an electronics & software guy.

Tittarelli, A., Borgini, A., Bertoldi, M., De Saeger, E., Ruprecht, A., Stefanoni, R., … Crosignani, P. (2008). Estimation of particle mass concentration in ambient air using a particle counter. *Atmospheric Environment*, *42*(36), 8543–8548. https://doi.org/10.1016/j.atmosenv.2008.07.056

TSI Incorporated. (2014). Operation and Seervice Manual, DustTrak DRX Aerosol Monitor, Revision L, P/N 6001898, (December).

UE. (2008). Diretiva 2008/50/CE do Parlamento Europeu e do Conselho, de 21 de Maio, relativa à qualidade do ar ambiente e a um ar mais limpo na Europa. *European Journal of Operational Research*, L 152.

USEPA. (2014). Air Quality Index (AQI). *A Guide to Air Quality and Your Health*, (February), 12. Retrieved from http://airnow.gov/index.cfm?action=aqibasics.aqi

Velasco, A., Ferrero, R., Gandino, F., Montrucchio, B., & Rebaudengo, M. (2016). A Mobile and Low-Cost System for Environmental Monitoring: A Case Study. *Sensors*, *16*(5), 710. https://doi.org/10.3390/s16050710

Villani, M.-G., Cignini, F., Ortenzi, F., Suriano, D., & Prato, M. (2016). The Smart Ring Experience in l'Aquila (Italy): Integrating Smart Mobility Public Services with Air Quality Indexes. *Chemosensors*, *4*(4), 24. https://doi.org/10.3390/chemosensors4040024

Wallace, L., & Ott, W. (2011). Personal exposure to ultrafine particles. *Journal of Exposure Science & Environmental Epidemiology*, *21*(1), 20–30. https://doi.org/10.1038/jes.2009.59

Wang, Y., Li, J., Jing, H., Zhang, Q., Jiang, J., & Biswas, P. (2015). Laboratory Evaluation and Calibration of Three Low-Cost Particle Sensors for Particulate Matter Measurement. *Aerosol Science and Technology*, *49*(11), 1063–1077. https://doi.org/10.1080/02786826.2015.1100710

WAQI. (2017). Real-time World Air Quality Index. Retrieved January 5, 2017, from http://waqi.info/

Williams, R., Kilaru, V. J., Snyder, E. G., Kaufman, A., Dye, T., Rutter, A., … Hafner, H. (2014). Air Sensor Guidebook. *Epa/600/R-14/159*, (1), 1–5. https://doi.org/10.1017/CBO9781107415324.004

Wirwahn, J. A., & Bartoschek, T. (2016). Enhancement of a Citizen Driven Sensor Network : Usability Engineering for Successful Open Citizen Science Master ' s Thesis Draft, (March).

World-Health-Organization. (2016). Air Pollution. Retrieved July 20, 2016, from http://www.who.int/topics/air_pollution/en/

World Health Organization. (2016). Ambient Air Pollution: A global assessment of exposure and burden of disease. *World Health Organization*, 1–131. Retrieved from www.who.int.org

Yunusa, Z., Hamidon, M. N., Kaiser, A., & Awang, Z. (2014). Gas sensors: A review. *Sensors and Transducers*, *168*(4), 61–75. https://doi.org/10.13074/jent.2015.12.153163